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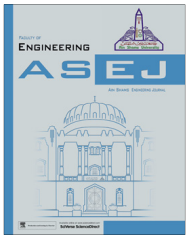

CIVIL ENGINEERING

Modeling the service life of slag concrete exposed to chlorides

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Abstract This paper focuses on the service life of slag concrete, where the time to corrosion initiation for a given chloride threshold value of 0.3% by mass of cement and different surface chloride concentrations (C_s), (1%, 3%, and 5%) was calculated using the error function solution to Fick's second law of diffusion as a service life model, where the chloride diffusion coefficients of different OPC/slag mixes were collected from literature.

To gain improved understanding of the above-mentioned aspect, this research presents an experimental investigation to elucidate the impacts of local by-product water cooled slag (WCS) on the microstructure of OPC cement paste mixes using thermo-gravimetric analysis and de-sorption approaches.

A partial replacement of OPC with 50% WCS in OPC paste mixes resulted in an increase in the amount of calcium silicate hydrate (CSH) by 57%, a decrease in the amount of calcium hydroxide (CH) by 66%, and a decrease in the amount of capillary pores by 57%, compared to those in the pure OPC matrix. In addition, the research results demonstrate that increasing C_s from 1% to 5% resulted in dramatically decreasing the service life of OPC/slag concrete, where the amount of decreasing reaches about 71%. Also, the service life of concrete increases with increasing slag content.

1. Introduction

Reinforced concrete is expected to show excellent durability; however, sometimes it does not perform adequately as a result of: inferior design, improper construction, inadequate materials selection, harsh environment, or a combination of these factors. Deterioration of reinforced concrete is the major problem facing the construction industry these days. Considerable resources have to be diverted toward the repair and rehabilitation of the deteriorated reinforced concrete structures. The two main causes of corrosion of steel in concrete are chloride

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attack and carbonation. These two mechanisms are unusual in that they do not attack the integrity of the concrete. Instead, these aggressive chemical species pass through the pores in the concrete and attack the steel.

Chloride-induced corrosion of the steel reinforcement is identified as the main cause of deterioration of different types of concrete structures (e.g., bridges, parking garages, off-shore platforms, etc.). The sources of chlorides are the seawater and deicing salts used during winter. The corrosion of the steel reinforcement leads to concrete fracture through cracking, delamination, and spalling of the concrete cover, reduction of concrete and reinforcement cross-sections, loss of bond between the reinforcement and concrete, and reduction in strength and ductility. As a result, the safety and serviceability of concrete structures are reduced [1].

A reliable prediction of the time to corrosion initiation of concrete structures exposed to chlorides is critical for the selection of a durable and cost-efficient design and for the optimization of the inspection and maintenance of built structures, which is essential to minimize the life cycle costs. Existing models are mostly based on the assumption of a Fickian process of diffusion for predicting the time and space variations of chloride content in concrete and on the concept of chloride threshold to define the corrosion resistance of reinforcing steel to chloride attack. Therefore, the governing parameters of this diffusion-based corrosion initiation time include the concrete cover depth, chloride diffusion coefficient in concrete, surface chloride concentration, and chloride threshold level assuming the presence of moisture and oxygen for the corrosion to proceed [1].

However, a considerable level of uncertainty may be associated with one or more of the above identified parameters. This is due to: (i) heterogeneity and aging of concrete with temporal and spatial variability of its chloride diffusivity; (ii) variability of concrete cover depth, which depends on quality control, workmanship, and size of structure; (iii) variability of surface chloride concentration, which depends on the severity of the environmental exposure; and (iv) uncertainty in chloride threshold level that depends on the type of reinforcing steel, type of cementing materials, test methods, etc. [2]. It is clear that the combination of these uncertainties leads to a considerable uncertainty in the model output, i.e., the time to corrosion initiation. This uncertainty in the model output could have serious consequences in terms of reduced service life, inadequate planning of inspection and maintenance, and increased life cycle costs.

The corrosion of concrete structures can be described as a two-stage process: (i) corrosion initiation stage; and (ii) corrosion propagation stage [3]. For chloride-induced corrosion, the initiation stage corresponds to the period of time during which chlorides penetrate the concrete but no damage is observed. The corrosion initiation time is defined as the time at which the concentration of chlorides at the steel surface reaches a critical or threshold value.

The propagation stage corresponds to the period of time during which corrosion products accumulate and initiate fracture of concrete and ultimately failure. The service life of concrete structures in chloride-laden environments can be defined as the sum of the durations of the two stages. In general, the durability and serviceability of concrete structures depend greatly on the duration of the initiation stage. As a result, a reliable prediction model of chloride penetration into a reinforced concrete structure is of utmost importance in predicting the time to corrosion initiation, as well as the total service life.

Aggressive agents such as chlorides, water, and oxygen penetrate into concrete through the pore spaces in the cement paste matrix and micro-cracks. The rate of penetration is dependent primarily on the quality of concrete and more particularly on the water–cement ratio of the concrete mix and the presence of supplementary cementing materials (e.g., silica fume, fly ash, or slag) and/or protective systems that delay or slow down chloride ingress. In porous solids, such as concrete, moisture may flow via the diffusion of water vapor, and via non-saturated or even saturated capillary flow in finer pores [4].

A little attention has been directed toward clarifying the relationship between W/B ratios, slag content, concrete cover depth, chloride threshold value, apparent chloride diffusion coefficient, and surface chloride concentrations. Having a good understanding to such aspects and their relationships to each other could provide a good base for reducing the risk of degradation of concrete, consequently prolonging its service life and reducing the running cost (maintenance).

In this study, the error function solution to Fick's second law of diffusion was used a service life model to evaluate the variations in the time to corrosion initiation of slag concrete caused by variations in the input data of the model, which include concrete cover depth, chloride diffusion coefficient, surface chloride concentration, chloride threshold level, water/binder ratio, and slag content. The error function solution as applied by Crank [5] may be stated as

$$C = C_0\left\{1 - erf\left(\frac{x}{2\sqrt{D_{ca}t}}\right)\right\} \quad (1)$$

$C_{(x,t)}$ is the chloride concentration at depth and time, C_o the surface chloride concentration, D_{ca} the apparent diffusion coefficient, t the time for diffusion, x the concrete cover depth, and erf is the statistical error function.

When $C_{(x,t)}$ is set equal to the chloride corrosion initiation concentration (chloride threshold value) and Eq. (1) is solved for t, the time for diffusion of chloride ions to the chloride corrosion initiation concentration can be determined.

Therefore, the present study was undertaken with the following objectives:

1. To investigate impacts of water-cooled slag (WCS) contents on hydration products and amount of interconnected pores (capillary porosity) of OPC matrix.
2. To clarify the relationship between W/B ratios, slag content, concrete cover depth, chloride threshold value, apparent chloride diffusion coefficient, surface chloride concentration and their impacts on the service life (in terms of time to corrosion initiation) of OPC/slag concrete.

2. Experimental

2.1. Materials, slag preparation, and mix proportions

Local ordinary Portland cement (OPC) complying with BS 12 (1978) and ESS 4756-1 (2006) was utilized throughout the work. Local water-cooled slag (WCS) was considered. The chemical analysis and surface areas of OPC and WCS are listed in Table 1.

Table 1 Chemical analysis and surface areas of OPC and WCS.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI	Surface area (m^2/g)
OPC	21.51	6.01	2.54	66.3	1.5	0.62	0.21	1.81	2.61	0.37
WCS	44.05	13.78	1.73	36.2	0.3	0.6	0.15	2.07	0.23	6.4

Three OPC paste mixes was prepared, using different WCS contents (0%, 30% and 50%, by weight of OPC) and water/binder of 0.4%.

2.2. Preparation of test samples

Mixing the cement paste was carried out manually, till complete homogeneity of mixes was achieved. Circular cement paste disks of thickness 5 mm and 50 mm diameter were then prepared for microstructure analysis (using thermo-gravimetric and de-sorption approaches). After casting, all molded samples were covered with plastic sheets for 24 h and then immersed in water curing tank (20 ± 2 °C) till the age of testing.

2.3. Test techniques

2.3.1. De-sorption test

This test was used to estimate the amount of interconnected pores (capillary porosity), as described by Ngala et al. [6] and Parrott [7]. The saturated specimens specified for this study were dried at 90.7% relative humidity by placing them above saturated salt solution of barium chloride contained in a desiccator until a near-constant sample weight was obtained. The weight loss on drying was then converted to volume fraction of the bulk paste. This particular capillary porosity corresponds to pores wider than about 30 nm. The Full details of the techniques and procedures of this test are described in [6–8]. The average capillary porosity results were calculated using five specimens.

2.3.2. Thermo-gravimetric analysis

The hardened cement paste specimens specified for this study were subjected to thermo-gravimetric analysis (TGA), by monitoring the % weight loss (% decomposition) that takes place as a result of raising temperature according to a defined regime. Previous studies found that calcium silicate hydrate (CSH) and calcium hydroxide (CH) decompose at a range of temperature of 110–250 °C and 450–600 °C, respectively [9,10]. Therefore, the amount of CSH and CH can be expressed as a function of the difference in the % weight loss occurred at these defined range of temperatures [10].

Following this concept, the hardened cement paste samples were subjected to a wide range of temperature increase and the weights were recorded at 110, 250, 450, and 600 °C. The % weight loss due to decomposition of CSH and CH were consequently estimated for all tested samples. Details of this analysis are described in [10]. The average results of these abovementioned parameters for five samples were calculated.

3. Results and discussion

Prior to studying the impact of utilizing slag on service life of concrete, the microstructure of OPC hardened cement paste containing such type of cement replacement material has been firstly investigated, to clarify its role on the hydration products and pore structure. Two approaches were, therefore, adopted, thermo-gravimetric analysis and de-sorption test, to elucidate the hydration products and pore structure of such matrix. These approaches were adopted in the literature and found to be reliable, simple, and cheap techniques for characterizing the microstructure of OPC matrix [6–10].

3.1. Microstructure of OPC/slag matrix

3.1.1. Hydration products

The results obtained from thermo-gravimetric analysis for the different hardened OPC pastes made with WCS are shown in Figs. 1 and 2. It is apparent from the results shown in Fig. 1 that the amount of CSH increases with increasing slag content, where the increasing amount of CSH at 30 and 50% slag replacement levels reaches about 29 and 57%, respectively, compared to the corresponding amount in the pure OPC matrix. Also, it is obvious from the results shown in Fig. 2 that the amount of CH decreases with increasing slag content, where the decreasing amount of CH at 30% and 50% slag replacement levels reaches about 47% and 66%, respectively, compared to the corresponding amount in the pure OPC matrix. The increase in CSH and the decrease in CH may be due to the pozzolanic reaction of WCS which combines with $Ca(OH)_2$ resulted from the hydration of OPC to form a fine CSH [11].

3.1.2. Pore structure

The results obtained by de-sorption test for the different OPC hardened cement pastes made with various slag contents are shown in Fig. 3. As seen, the amount of capillary porosity decreases with increasing slag content, where the decreasing amount of capillary porosity at 30% and 50% slag replacement levels reaches about 30 and 57%, respectively, compared to the corresponding amount in the pure OPC matrix. The decrease in the capillary porosity may be attributed to the fact that the slag retains the alkali and calcium hydroxides in its hydration products, forming new CSH phase with dense structure and finer pore sizes than that equivalent OPC paste [12]. It can also be attributed to the participation of the pozzolanic reaction's product on pathways between pores, leading to a

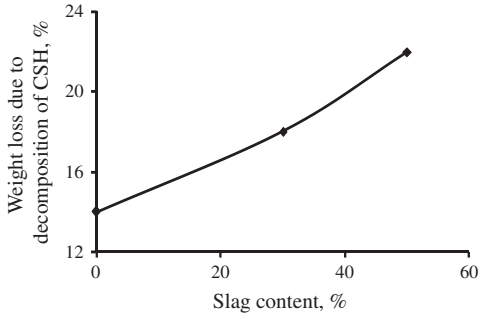

Figure 1 CSH of OPC/slag pastes.

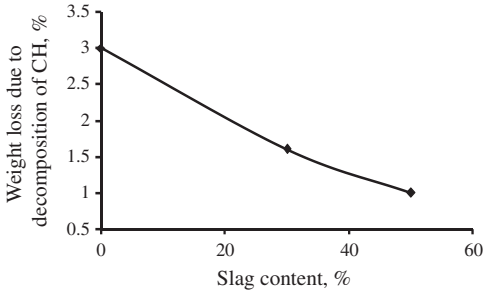

Figure 2 CH of OPC/slag pastes.

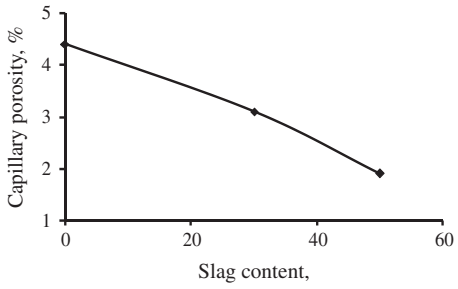

Figure 3 Capillary porosity of OPC/slag pastes.

reduction in the amount of interconnected pores (capillary porosity).

The results obtained from the de-sorption test agree with those obtained from thermo-gravimetric analysis test, where an increase in the amount of CSH and a decrease in the amount of CH were produced for WCS/OPC mixes. This affirms that the unoccupied spaces within the paste matrix were filled with the pozzolanic reaction products, thus reducing the amount of continuous pores (capillary pores).

Generally, it can be stated that the considered local by-product material (slag) has shown a considerable efficiency on the microstructure of OPC matrix. A positive effect for such type of cement replacement material on altering the amount of hydration product and reducing the amount of interconnected pores was found.

3.2. Service life of OPC/slag concrete

The application of the error function solution to Fick's second law of diffusion as a chloride ingress model requires the determination of a number of variables. These variables include apparent chloride diffusion coefficients, service life, concrete cover depth, corrosion threshold values, and notional surface chloride concentrations. The values used in application of error function solution model are outlined as follows:

3.2.1. Apparent chloride diffusion coefficients

The apparent chloride diffusion coefficients of OPC/slag mixes made with different slag contents (0%, 30%, and 50%, by mass of OPC) and various water/binder ratios (0.37%, 0.42%, and 0.47%) were collected from literature [13] and outlined in Table 2.

3.2.2. Concrete cover depth

Concrete covers of 0.03, 0.04, 0.05, 0.06, and 0.07 m were adapted in this study.

3.2.3. Corrosion threshold value

Corrosion threshold value of 0.3% by mass of cement was used in this research.

3.2.4. Surface chloride concentration

A large range of notional surface chloride concentration values has been found in reported results. Varying environmental conditions from country to country may be responsible for the large range. Surface chloride concentrations of 1%, 3%, and 5% were considered in this study.

3.2.4.1. Effect of slag on the service life of OPC/slag concrete. Fig. 4 illustrates the service life of the different OPC/slag mixes made with different W/B ratios (0.37%, 0.42%, and 0.47%) and different slag contents (0%, 30%, and 50% by mass of OPC). The time to corrosion initiation was calculated for a given chloride threshold value of 0.3% by mass of cement, concrete cover depth equal to 0.07 m and a surface chloride concentration of 1%. As seen, the incorporation of slag in concrete mixes of different W/B ratios resulted in a reasonable increase in the time to corrosion initiation. The amount of increase in the service life of OPC/30% slag mixes made with 0.37%, 0.42%, and 0.47% W/B ratios reaches about 1.39%, 1.36%, and 1.49%, respectively. While the amount of increase in the service life of OPC/50% slag mixes made with 0.37%, 0.42% and 0.47% W/B ratios reaches about 2.0%, 1.74% and 1.62%, respectively, compared to that of pure OPC concrete.

The results shown in Fig. 4 agree with those obtained from the de-sorption and thermo-gravimetric analysis tests where a reduction in the capillary porosity and the amount of CH of

Table 2 Shows the set of D_{ca} values that were used in study.

Mix code	OPC (%)	GGBS (%)	W/B ratio (%)	$D_c \times 10^{-11}$ m^2/s
1	100	0	37	1.3
2	100	0	42	1.5
3	100	0	47	1.8
10	70	30	37	0.93
11	70	30	42	1.1
12	70	30	47	1.2
13	50	50	37	0.63
14	50	50	42	0.86
15	50	50	47	1.1

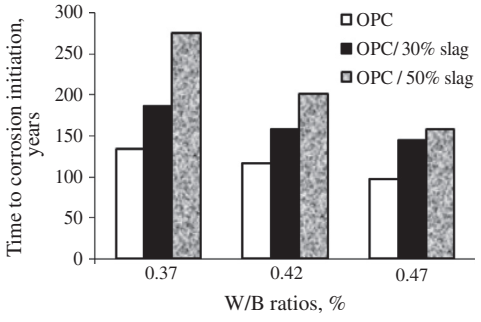

Figure 4 Time to corrosion initiation of OPC/slag concrete (concrete cover equal to 0.07 m, surface chloride concentration of 1%).

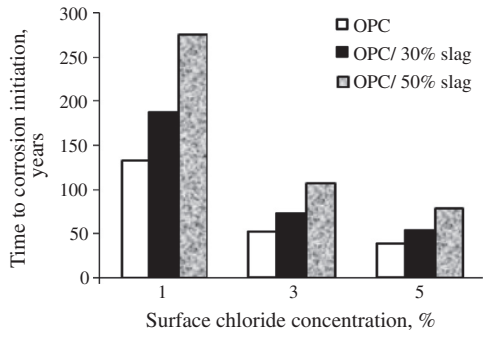

Figure 5 Time to corrosion initiation of OPC/slag concrete (concrete cover equal to 0.07 m).

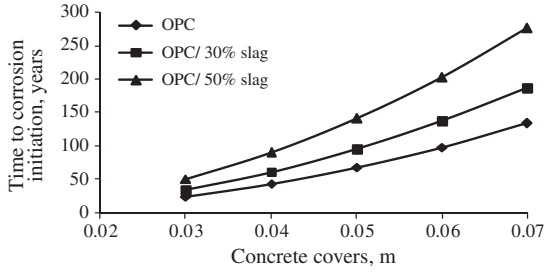

Figure 6 Time to corrosion initiation of OPC/slag concrete (surface chloride concentration of 1%).

slag mixes was found, compared to that of pure OPC mix. And hence, a reasonable reduction in the time to corrosion initiation of OPC/slag concrete was found.

Fig. 5 demonstrates that the service life of the different OPC/slag mixes made with 0.37% W/B ratio and different slag contents (0%, 30%, and 50% by mass of OPC). The time to corrosion initiation was calculated for a given chloride threshold values of 0.3% by mass of cement, concrete cover depth equal to 0.07 m and different surface chloride concentrations of (1%, 3%, and 5%). As seen, increasing the surface chloride concentration resulted in reasonably decreasing the service life of OPC/slag concrete. The amount of decrease in the service life of OPC/30% slag concrete exposed to surface chloride concentrations of 3% and 5% reaches about 61% and 71%, respectively, compared to that of OPC/30% slag concrete exposed to surface chloride concentration of 1%.

Fig. 6 demonstrates that the service life of the different OPC/slag mixes increases with increasing concrete cover depth, where considering concrete cover depth of 0.07 m can increase the service life by a factor of about 5.5, compared with that of 0.03 m concrete cover depth.

4. Conclusions

The main conclusions of this study can be summarized as follow:

1. Inclusion of local by-product slag that is cooled by water (WCS), in OPC matrix has a positive effect on the microstructure of concrete, where a partial replacement of OPC with 50% WCS in OPC paste mixes resulted in an increase in the amount of calcium silicate hydrate (CSH) by 57%, a decrease in the amount of calcium hydroxide (CH) by 66%, and a decrease in the amount of capillary pores by 57%, compared to those in the pure OPC matrix.
2. The benefits of slag inclusion were clearly demonstrated and could provide a good margin of safety in satisfactory service life prediction.
3. Increasing the surface chloride concentration from 1% to 5% decreases the service life of OPC/slag concrete, where the amount of decrease reaches about 71%.
4. The service life of OPC/slag concrete increases with increasing concrete cover depth, where considering concrete cover depth of 0.07 m can increase the service life by a factor of about 5.5, compared with that of 0.03 m concrete cover depth.

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